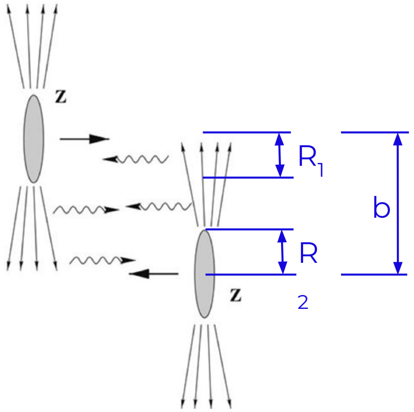
Upcgen: an event generator for two-photon and photoproduction processes in ultraperipheral collisions

Nazar Burmasov[1,2,3], Evgeny Kryshen[1,2]

[1]NRC "Kurchatov Institute" - PNPI, Gatchina
[2]Joint Institute for Nuclear Research, Dubna
[3]National Research Nuclear University "MEPhI", Moscow

July 4th, 2025, NUCLEUS-2025, St. Petersburg

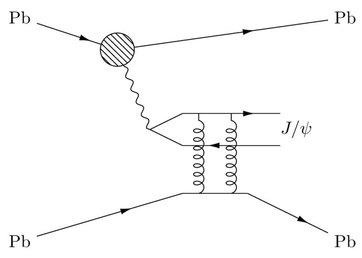
Ultraperipheral collisions of heavy ions



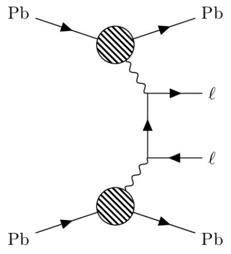
- ➔ Hadronic interactions strongly suppressed
- ➔ Photon-induced reactions dominate
- ➔ Huge EM field $\propto Z^2$ → high event rates!

Unique tool for studies:

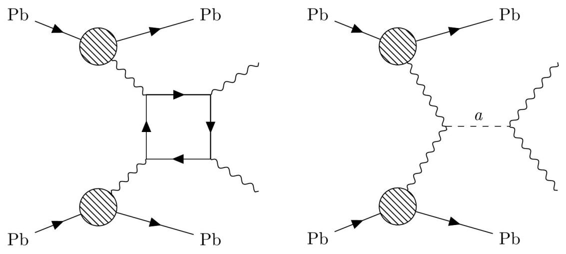
- ➔ Probing parton density functions with vector mesons
- ➔ Tau anomalous magnetic moment, testing QED in strong EM fields
- ➔ And more - rare processes, search for new physics



Vector mesons

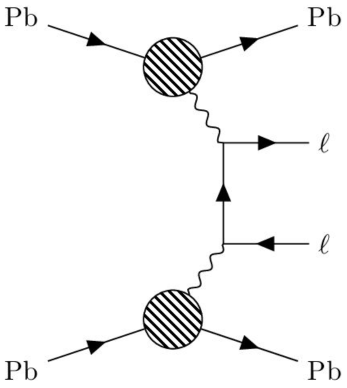


Dileptons



Light-by-light scattering and ALPs

Two-photon processes



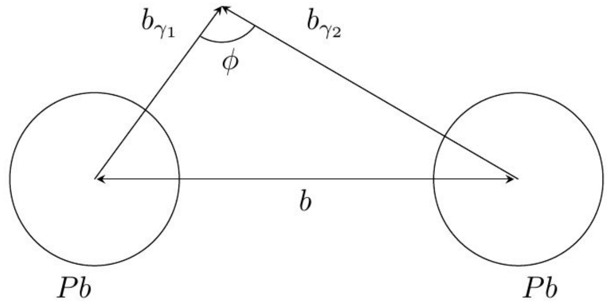
Dileptons

Cross sections of two-photon reactions

Total cross section

Elementary cross section

$$\frac{\mathrm{d}^2\sigma(AA\to AA+X)}{\mathrm{d}Y\,\mathrm{d}M} = \frac{\mathrm{d}^2 N_{\gamma\gamma}}{\mathrm{d}Y\,\mathrm{d}M}\sigma(\gamma\gamma\to X)$$



Two-photon luminosity

Fluxes

$$\frac{\mathrm{d}^2 N_{\gamma\gamma}}{\mathrm{d}k_1\mathrm{d}k_2} = \int\!\!\int \mathrm{d}^2 b_{\gamma_1}\mathrm{d}^2 b_{\gamma_2}\,\Gamma_{AA}(b)\,N_{\gamma A}(k_1,b_{\gamma_1})\,N_{\gamma A}(k_2,b_{\gamma_2})$$

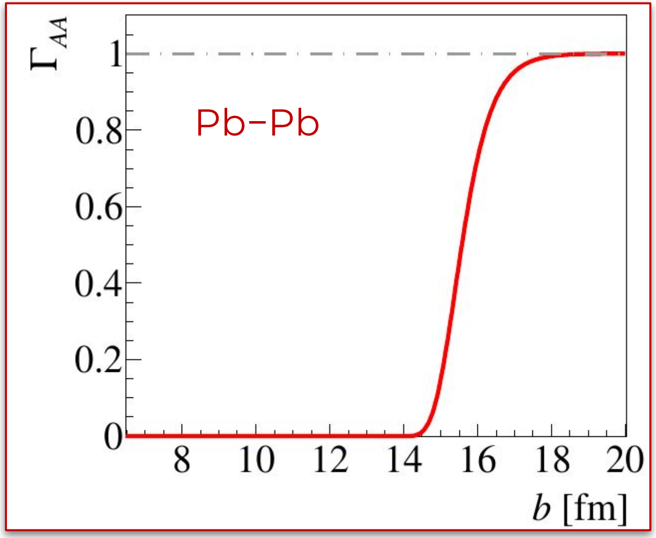
$$k_{1,2} = \frac{M}{2}\exp(\pm Y)$$

Probability of no hadronic interactions

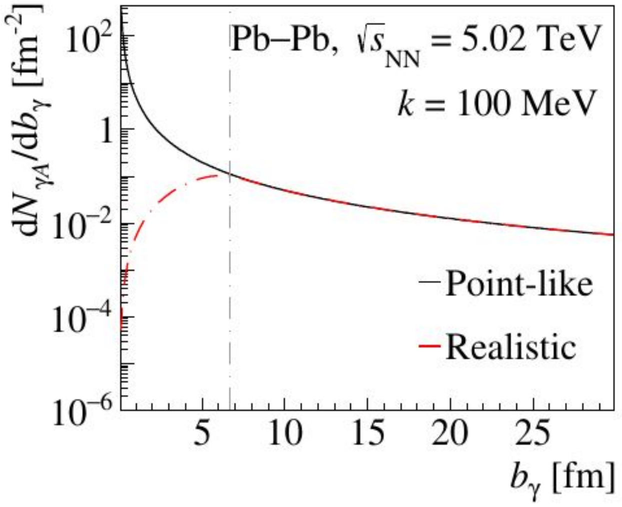
$$\Gamma_{AA}(b) = \exp\left(-\sigma_{NN}^{\mathrm{tot}}\int \mathrm{d}^2\vec{b}'\,T_A(|\vec{b}'|)\,T_A(|\vec{b}-\vec{b}'|)\right)$$

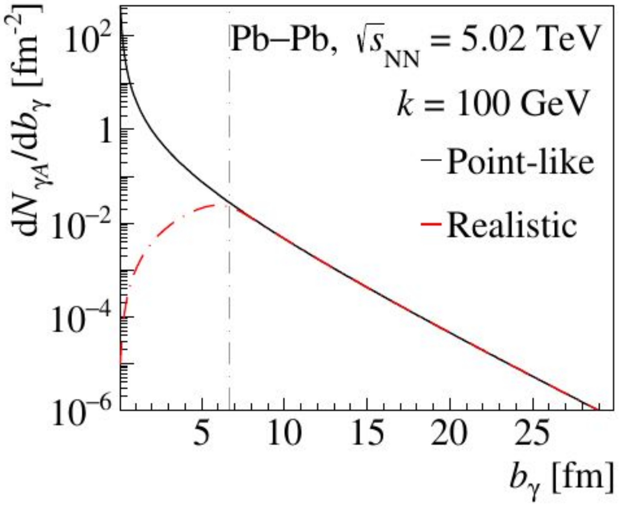
$$T_A(b) = \int \mathrm{d}z\,\rho(b,z)$$

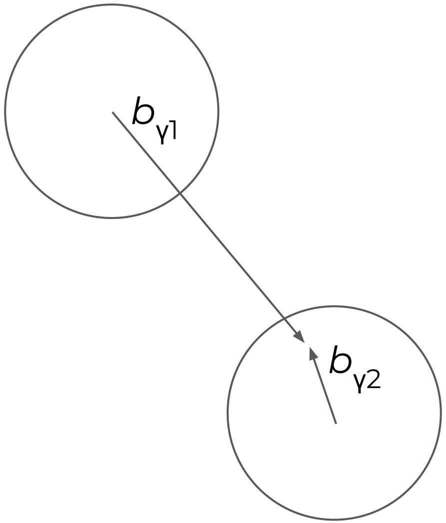
Nuclear density modelled with Woods-Saxon distribution



Fluxes with realistic and point-like sources







Point-like source

$$N_{\gamma A}(k, b_\gamma) = \frac{Z^2 \alpha k^2}{\gamma^2 \pi^2} \left[K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right]$$

$$x = k b_\gamma / \gamma$$

Realistic nuclear form-factor

$$N_{\gamma A}(k, b_\gamma) = \frac{Z^2 \alpha}{\gamma \pi^2} \left| \int \frac{\mathrm{d}k_\perp k_\perp^2}{k_\perp^2 + k^2/\gamma^2} F_{\mathrm{ch}}(k_\perp^2 + k^2/\gamma^2)\, J_1(b_\gamma\, k_\perp) \right|^2$$

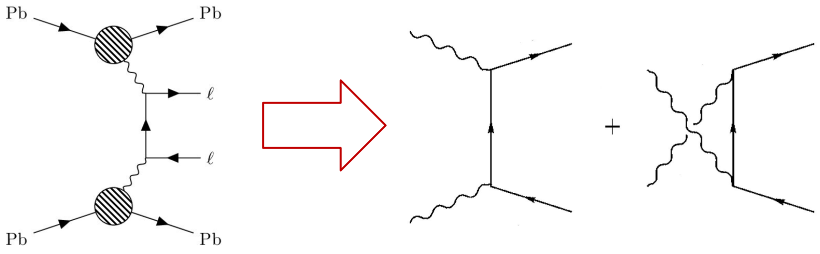
➔ Significant difference at small photon impact parameters!

Dilepton production

Elementary cross section

$$\frac{d\sigma(\gamma\gamma\to\ell\ell)}{dz} = \frac{2\pi}{64\pi^2 s}\frac{|\vec{p}_\ell|}{|\vec{p}_\gamma|}\frac{1}{4}\sum_{\text{spin}}|\mathcal{M}|^2$$

$$z = \cos\theta$$



Amplitude

$$\mathcal{M} = (-i)\,\epsilon_{1\mu}\epsilon_{2\nu}\,\bar{u}(p_3)\left(i\Gamma^{(\gamma\ell\ell)\,\mu}(p_1)\frac{i(\not{p}_t+m_\ell)}{p_t^2-m_\ell^2+i\epsilon}i\Gamma^{(\gamma\ell\ell)\,\nu}(p_2) + i\Gamma^{(\gamma\ell\ell)\,\nu}(p_2)\frac{i(\not{p}_u+m_\ell)}{p_u^2-m_\ell^2+i\epsilon}i\Gamma^{(\gamma\ell\ell)\,\mu}(p_1)\right)v(p_4)$$

Vertex function

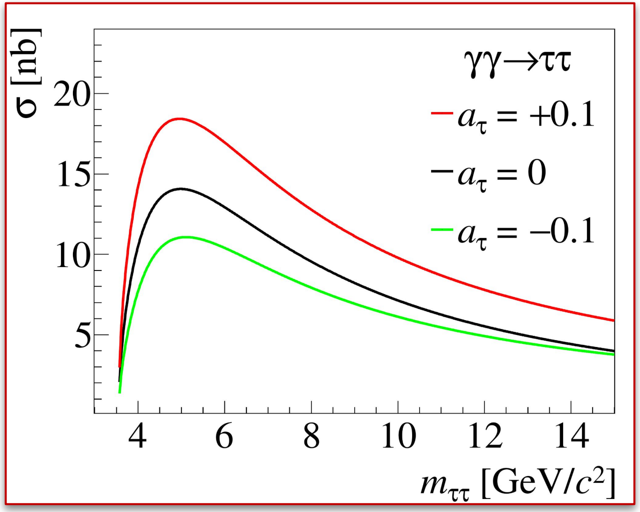
$$i\Gamma_\mu^{(\gamma\ell\ell)}(q) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2(q^2)\right]$$

At small *q* limit, well-fulfilled in ultraperipheral collisions:

$$q^2 \to 0 \quad F_1(0) = 1 \quad F_2(0) = a_\ell$$

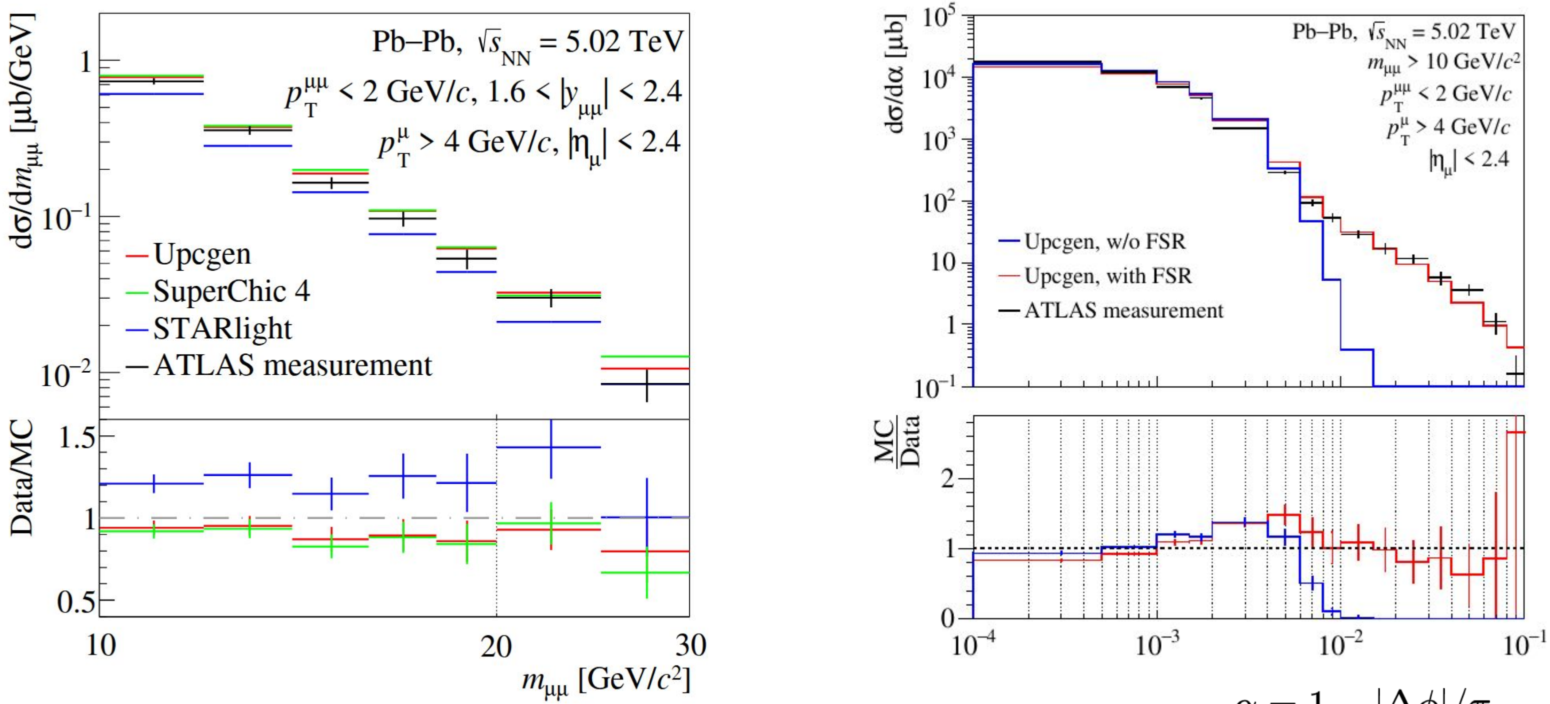
Breit-Wheeler formula for $a_\ell = 0$

$$\frac{d\sigma}{dz} = \frac{\pi\alpha^2}{s}\beta\left(2 + 4\beta^2\frac{\beta^2(1-z^2)z^2+1-\beta^2}{(1-\beta^2 z^2)^2}\right) \qquad \beta^2 = 1 - \frac{4m_\ell^2}{s}$$



Dimuon production in ATLAS at 5.02 TeV

Dimuons at ATLAS: PRC 104 (2021) 024906
STARlight: CPC, 212 (2017) 258-268
SuperChic: EPJC, 80 (2020) 925
Pythia8: CPC, 191 (2015) 159-177

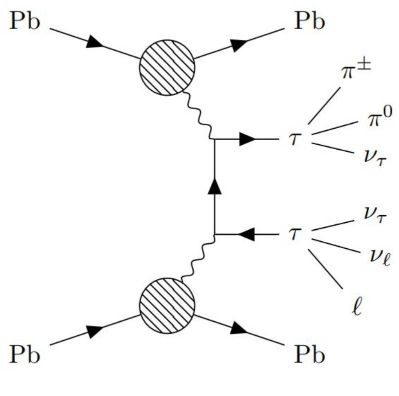


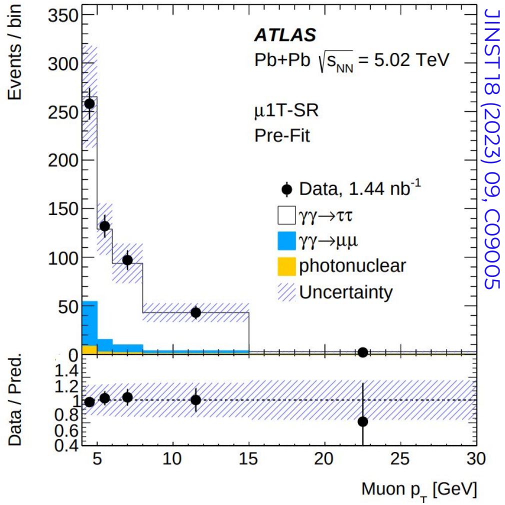
$$\alpha = 1 - |\Delta\phi|/\pi$$

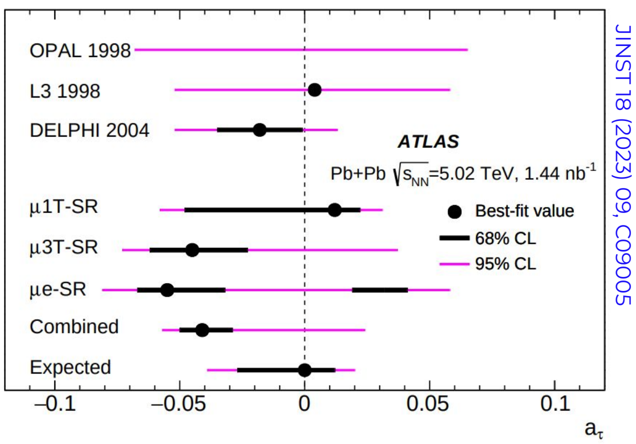
- STARlight: point-like flux, hard cut-off at $b_\gamma = R_A$
- SuperChic, Upcgen: realistic form-factor
- Good data description by Upcgen

- Additional simulation of final-state radiation effects in Pythia8 gives a good description of acoplanarity-dependent cross section

Tau anomalous magnetic moment with ALICE

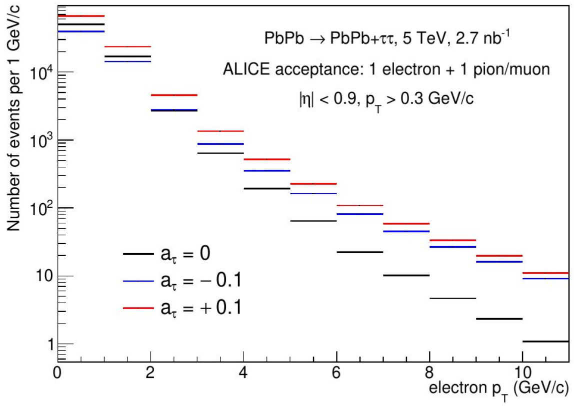


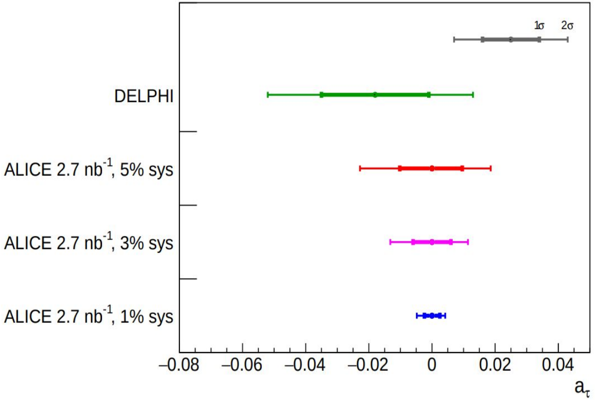




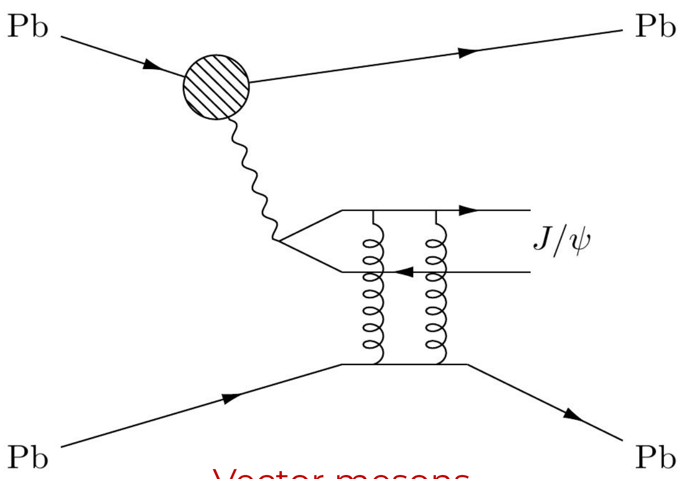
Sensitivity to a_τ in ALICE

- Upcgen+Pythia 8 for tau production simulations
- 1 electron + 1 π/μ, central barrel: $|\eta| < 0.9$, $p_T^e > 300$ MeV/c
- ALICE can set x2 better limits on a_τ compared to DELPHI





Photonuclear reactions



Vector mesons

Coherent vector meson photoproduction

Total cross section

Flux

$$\boxed{\frac{d\sigma_{AA\to AAV}(y)}{dy}} = \boxed{n_\gamma(y)}\boxed{\sigma_{\gamma A\to AV}(y)} + \boxed{n_\gamma(-y)}\boxed{\sigma_{\gamma A\to AV}(-y)}$$

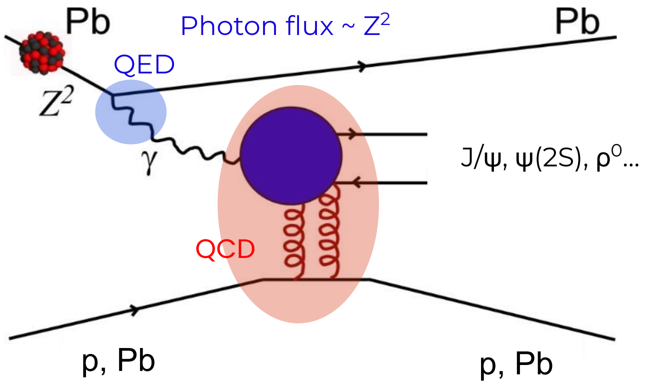
Photoproduction off nucleus

$$\sigma_{\gamma A\to VA}(W_{\gamma p}) = R_g^2(x,\mu^2)\sigma^{IA}_{\gamma A\to VA}(W_{\gamma p})$$

Gluon shadowing

$$R(x,\mu^2) = \frac{f_A(x,\mu^2)}{Af_N(x,\mu^2)}$$

$$W_{\gamma p} = \sqrt{2E_N m_V}e^{-y/2} \quad x = m_V^2/W_{\gamma p}^2 \quad \mu^2 = \frac{m_V^2}{4}$$



Impulse approximation - assuming no nuclear interactions

$$\sigma^{IA}_{\gamma A\to VA}(W_{\gamma p}) = \left.\frac{d\sigma_{\gamma p\to Vp}(W_{\gamma p})}{dt}\right|_{t=0} \Phi_A(t_{min})$$

Integral of squared nuclear form factor

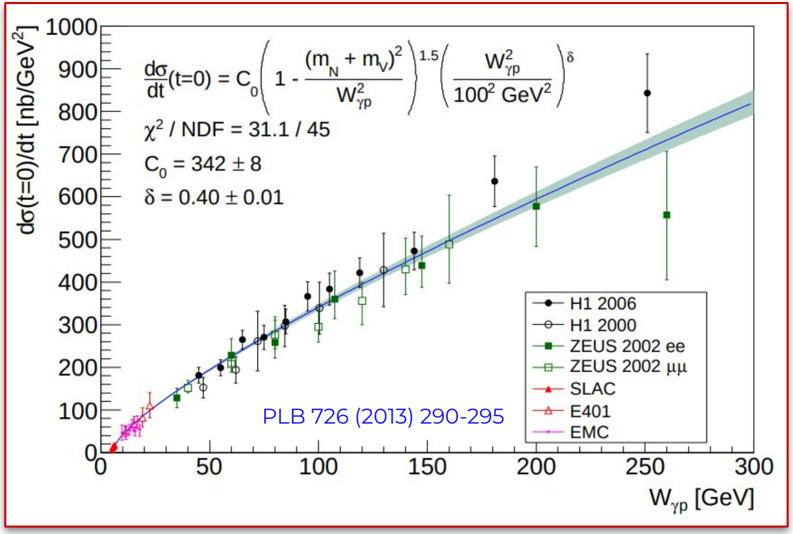
Photoproduction off proton

$$\left.\frac{d\sigma_{\gamma p\to Vp}(W_{\gamma p})}{dt}\right|_{t=0} = C_p(\mu^2)\alpha_s^2(\mu^2)[xg_p(x,\mu^2)]^2$$

Normalization

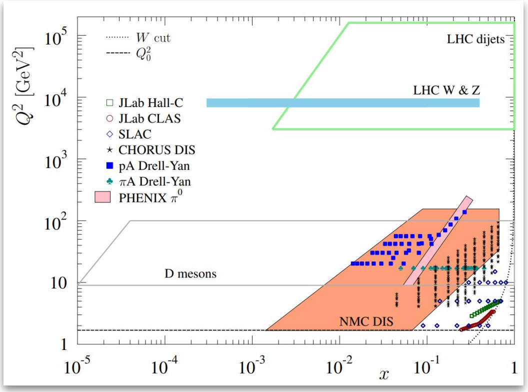
Gluon density in proton

Parametrization



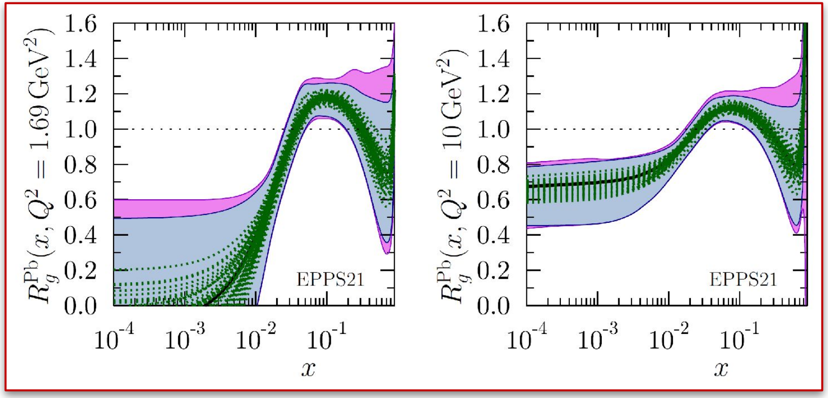
Gluon shadowing

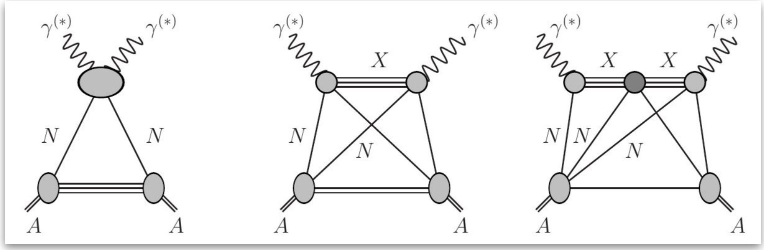
- Shadowing ~ suppressed cross sections in off-nucleus production



Global fits of data on Drell-Yan and DIS

EPPS21: EPJC 82 (2022) 413



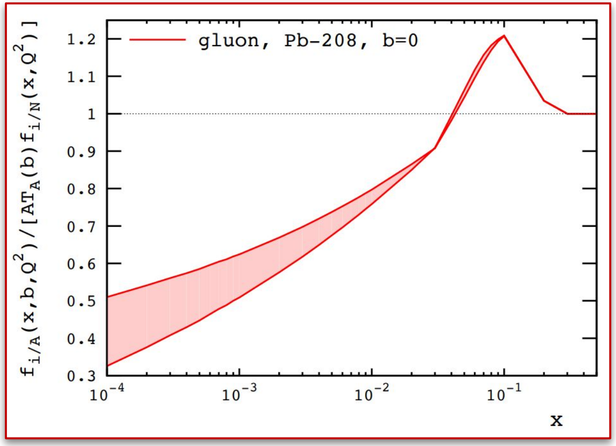


Leading Twist Approximation

Glauber-Gribov formalism for nucleon rescattering

+ intermediate diffractive states

Rept.Prog.Phys. 85 (2022) 12, 126301



Comparison with coherent J/ψ at the LHC

Overall:

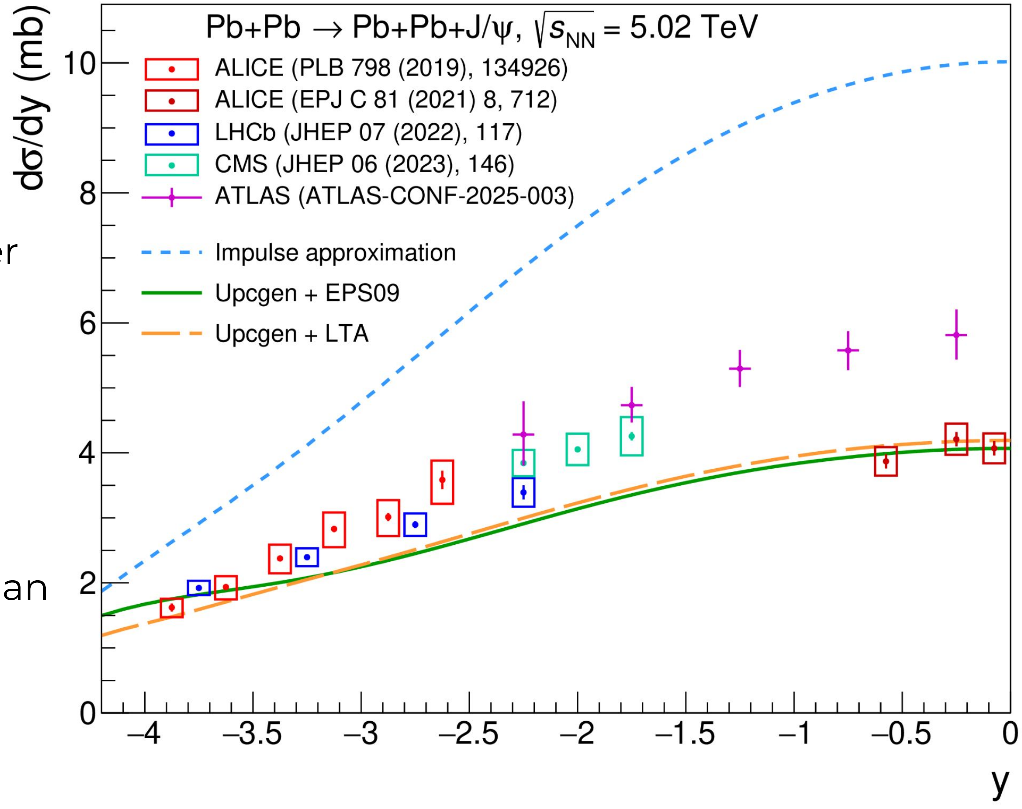
- ➔ Impulse approximation significantly overestimates data

At high rapidity:

- ➔ EPS09 fit of gluon shadowing gives better description
- ➔ Leading Twist Approximation works well, giving a slightly different result

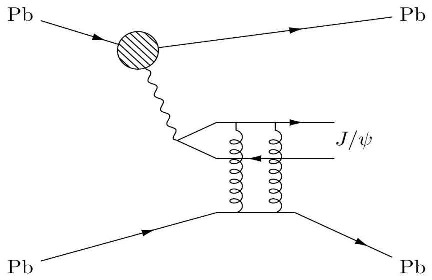
At midrapidity:

- ➔ New ATLAS results significantly higher than expected from EPS09 or LTA
- ➔ Significant tension with ALICE → investigation is needed

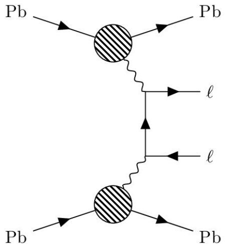


Summary

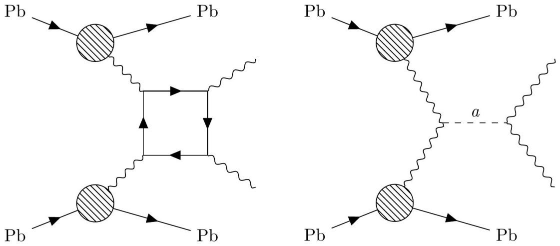
- Upcgen – useful tool for studies of photonuclear and two-photon processes:
  - Generator-level studies → feasibility of measurements
  - Realistic detector simulation
  - Theoretical predictions
- Implementation details: Comput.Phys.Commun. 277 (2022) 108388



Vector mesons



Dileptons



Light-by-light scattering and ALPs

Thank you for your attention!

Backup

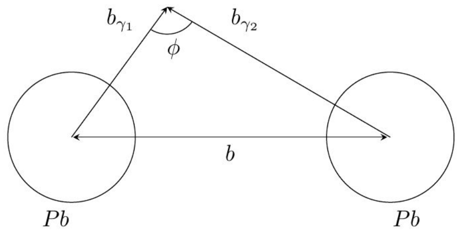
Photon polarization effects for dilepton production

- Polarization vectors of two colliding photons can be either parallel or perpendicular

Total cross section

‘Even’ elementary cross section

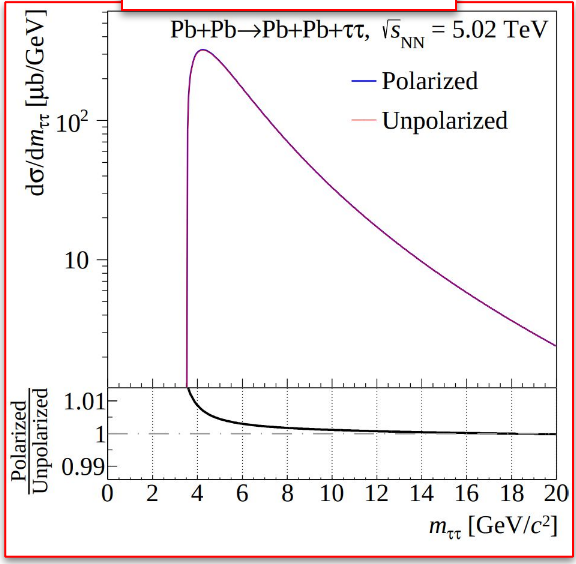
‘Odd’ elementary cross section



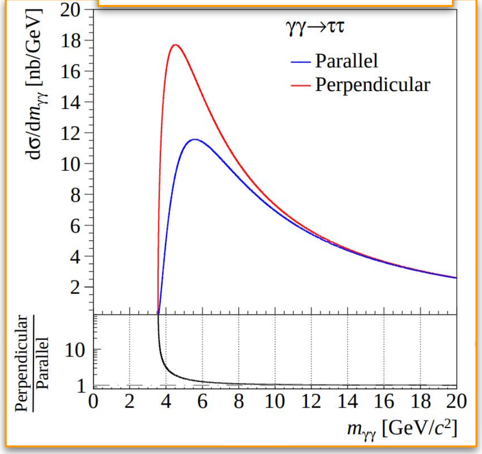
$$\frac{\mathrm{d}^2\sigma(AA \to AA+\ell\ell)}{\mathrm{d}Y\,\mathrm{d}M} = \frac{\mathrm{d}^2 N_{\gamma\gamma}^{||}}{\mathrm{d}Y\,\mathrm{d}M}\sigma^{||}(\gamma\gamma\to\ell\ell) + \frac{\mathrm{d}^2 N_{\gamma\gamma}^{\perp}}{\mathrm{d}Y\,\mathrm{d}M}\sigma^{\perp}(\gamma\gamma\to\ell\ell)$$

$$\frac{\mathrm{d}^2 N_{\gamma\gamma}^{[||,\perp]}}{\mathrm{d}k_1\mathrm{d}k_2} = \int\!\!\int \mathrm{d}^2 b_{\gamma_1}\mathrm{d}^2 b_{\gamma_2}\,\Gamma_{AA}(b)\,N_{\gamma A}(k_1,b_{\gamma_1})\,N_{\gamma A}(k_2,b_{\gamma_2})\left[\frac{|\vec{b}_{\gamma_1}\cdot\vec{b}_{\gamma_2}|^2}{b_{\gamma_1}^2 b_{\gamma_2}^2},\frac{|\vec{b}_{\gamma_1}\times\vec{b}_{\gamma_2}|^2}{b_{\gamma_1}^2 b_{\gamma_2}^2}\right]$$

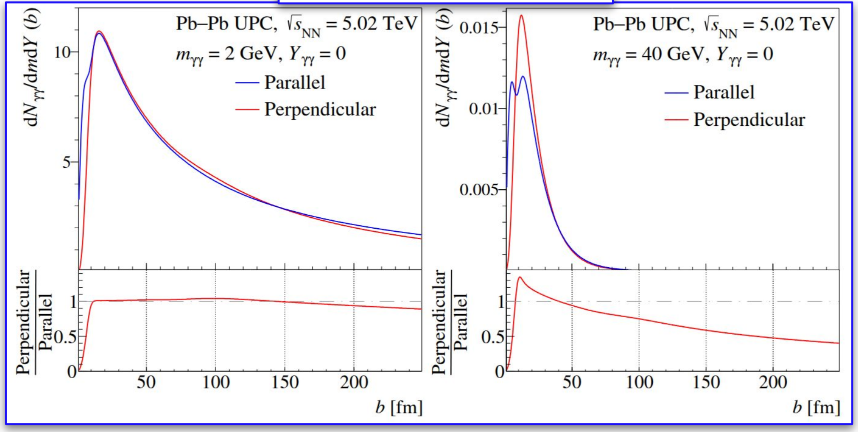
Total cross section



Elementary cross section



Two-photon luminosity



Light-by-light scattering

Elementary cross section

$$\frac{d\sigma(\gamma\gamma \to \gamma\gamma)}{dz} = \frac{1}{128\pi s}\left|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}\right|^2$$

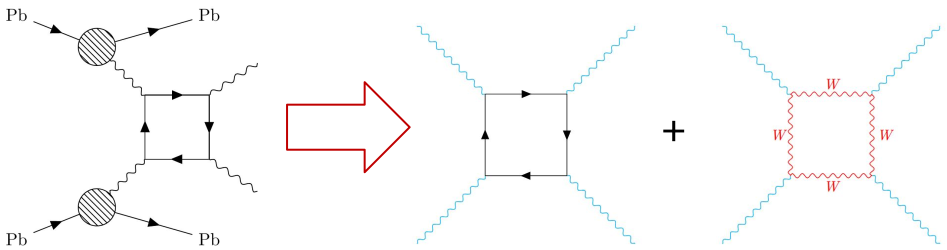
$$z = \cos\theta$$

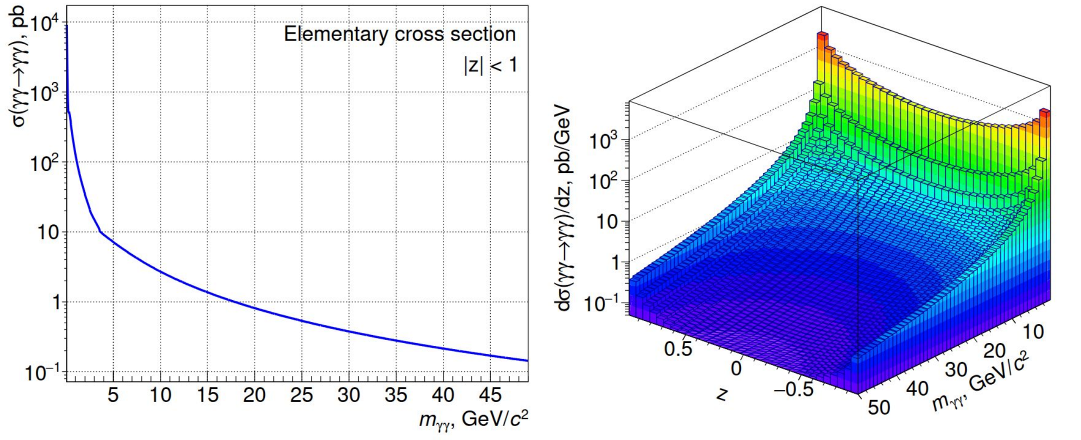
Amplitude

$$\mathcal{M}_{\gamma\gamma\to\gamma\gamma} = \sum_{fermions} \mathcal{M}^{fermions} + \mathcal{M}^{boson}$$

$$\begin{aligned}\mathcal{M}^{fermion}_{++++}(s,t,u) = C^f\Big\{ &-1 + \frac{u-t}{s}\Big[B_0(u,m_f) - B_0(t,m_f)\Big] \\ &+ \Big\{\frac{4\,m_f^2}{s} + \Big(\frac{t\,u}{s^2} - \frac{1}{2}\Big)\Big\}\Big[u\,C_0(u,m_f) + t\,C_0(t,m_f)\Big] \\ &- 2\,m_f^2\,s\,\Big(\frac{m_f^2}{s} - \frac{1}{2}\Big)\Big[D_0(s,t,m_f) + D_0(s,u,m_f) + D_0(t,u,m_f)\Big] \\ &- t\,u\,\Big(\frac{4\,m_f^2}{s} + \frac{t\,u}{s^2} - \frac{1}{2}\Big)\,D_0(t,u,m_f)\Big\},\end{aligned}$$

- ➔ B_0, C_0, D_0 are the 2- 3- and 4-point scalar one-loop integrals
- ➔ Boson amplitudes can be expressed through the fermion ones





Detailed description e.g. in Bohm, Schuster, Z. Phys. C 63 (1994), 219-225